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Aircraft ADS-B Verification and Validation (V&V)

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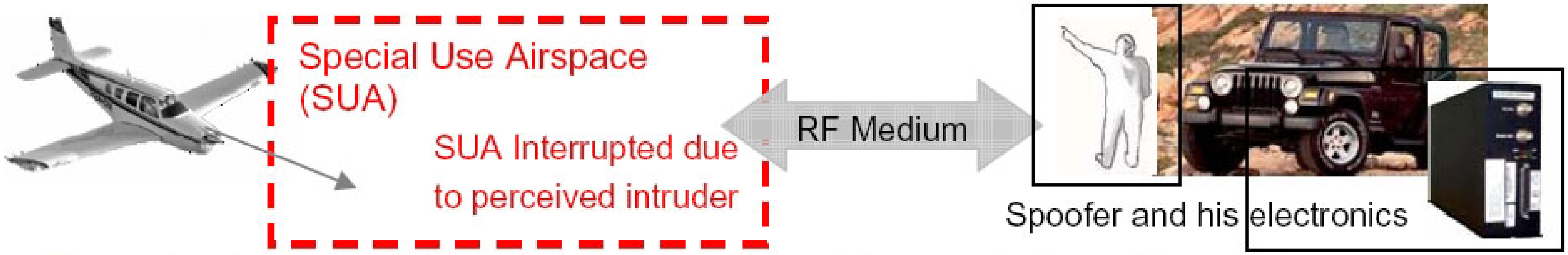
Motivation

- ADS-B is the Next Generation Surveillance in the National Airspace System (NAS)
- FAA Capstone Project (Alaska) & Ohio Valley Operational Evaluation (Midwest) have proven the benefits of ADS-B
- In some remote and/or mountainous regions (e.g., Alaska), ADS-B may be the Sole Source of Surveillance information
- There is a need to create a Verification and Validation (V&V) mechanism that is independent of a secondary surveillance source (e.g., SSR) in order for ADS-B to be a safe and reliable surveillance source

Example Spoof Scenario



- A Terrorist flies a GA Aircraft through <u>in</u>active SUA on a weekend and records Valid ADS-B data
- The Terrorist returns midweek and drives up a mountainside near the SUA; the SUA is active and the Terrorist disrupts Military Exercises within the SUA by broadcasting a Spoof ADS-B Signal from the mountainside
- Such a signal needs to be classified as Invalid

V&V Approach

- **State Verification – Using Kalman Filtering, establish a continuous state estimate of the ADS-B Aircraft being tracked**
- **Signal Conformance – Check to insure that the ADS-B Electronic Signal is arriving from the direction expected from ADS-B Target State information**
- **State & Intent Verification – Check two properties of the Aircraft relative to a Required Navigation Performance (RNP):**
  1. **Geometric Conformance**
     - **Based on Geometry only**
  2. **Intent Conformance**
     - **Based on Where the Pilot Intends to go in the near future**

ADS-B Reports

- We primarily use the ADS-B SV and TC Reports
- See RTCA ADS-B MASPS 242-A for Definitions

RTCA defined ADS-B State Vector (SV) Report

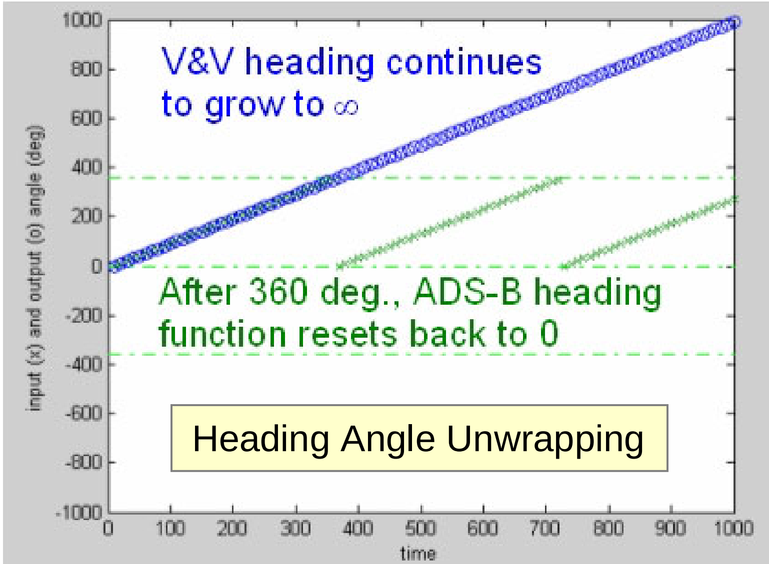
	Field	Contents
ID	1	Participant Address
	2	Address Qualifier
TOA	3	Time of Applicability
Geometric Position	4a	Latitude
	4b	Longitude
	4c	Horiz. Position Valid
	5a	Geometric Altitude
	5b	Geometric Altitude Valid
Horiz. Velocity	6a	North Velocity while airborne
	6b	East Velocity while airborne
	6c	Airborne Horizontal Velocity Valid
	7a	Ground Speed while on the surface
	7b	Surface Ground Speed Valid
Heading	8a	Heading while on the Surface
	8b	Heading Valid
Baro Altitude	9a	Pressure Altitude
	9b	Pressure Altitude Valid
Vertical Rate	10a	Vertical Rate
	10b	Vertical Rate Valid
NIC	11	Navigation Integrity Category
Report Mode	12	SV Report Mode

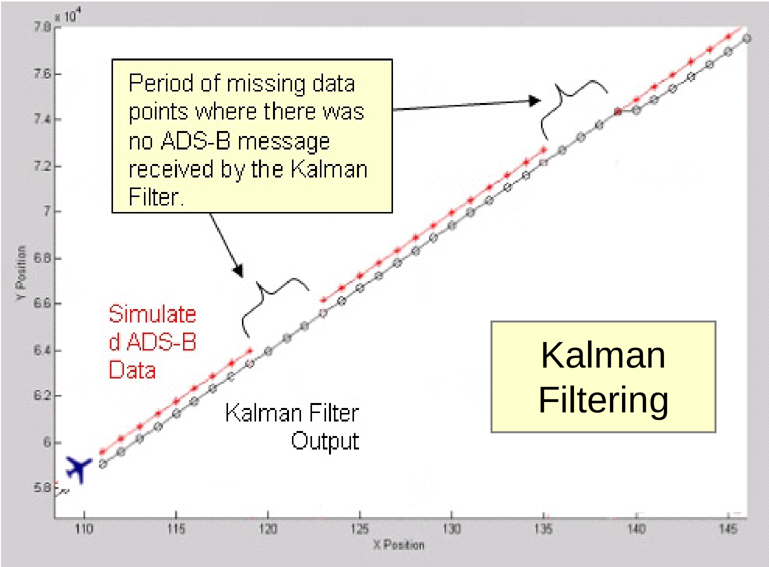
RTCA defined ADS-B Trajectory Change (TC) Report

	Field	Contents
ID	1	Participant Address
	2	Address Qualifier
TOA	3	Time of Applicability (1 sec resolution)
TC Report #	4	TC Report Sequence Number
TC Report Version	5a	TC Report Cycle Number
	5b	Reserved for TC Management Indicator
TTG	6	Time To Go (TTG)
Horiz. TC Report Info.	7a	Horiz. Data Available & Horiz. TC Type
	7b	TC Latitude
	7c	TC Latitude
	7d	Turn Radius
	7e	Track to TCP
	7f	Track from TCP
	7g	Reserved for Horiz. Conformance
	7h	Horiz. Command/Planned Flag
Vertical TC Report Info.	8a	Vertical Data Available & Vert. TC Type
	8b	TC Altitude
	8c	TC Altitude Type
	8d	Reserved for Altitude Constraint Type
	8e	Reserved for Able/Unable Altitude Constraint
	8f	Reserved for Vertical Conformance
	8g	Vertical Command/Planned Flag

State Verification

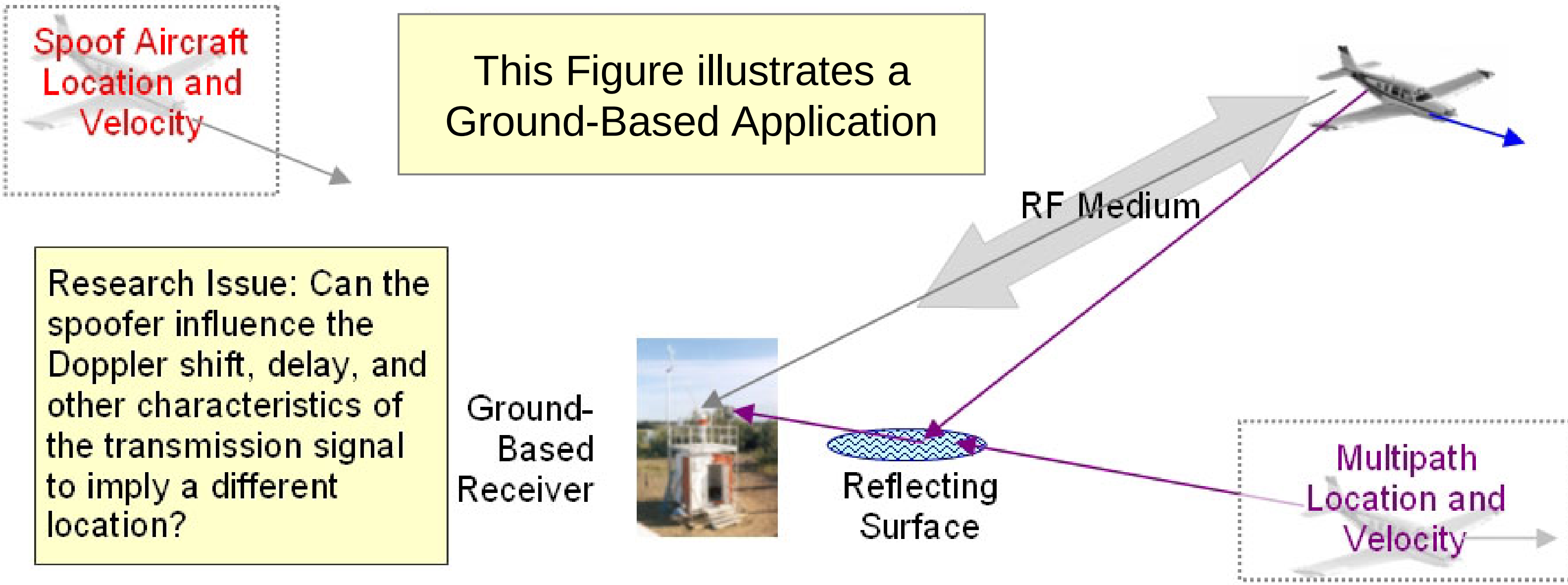
- Input Data Manipulation:
  - Unwrapping
  - Units Conversions
  - Bad Data Point Flagging
  - Missing Data Identification
- Kalman Filtering:
  - Bad Data Point Elimination
  - State Estimation
  - Noise Filtering
  - Coasting over Missing Data





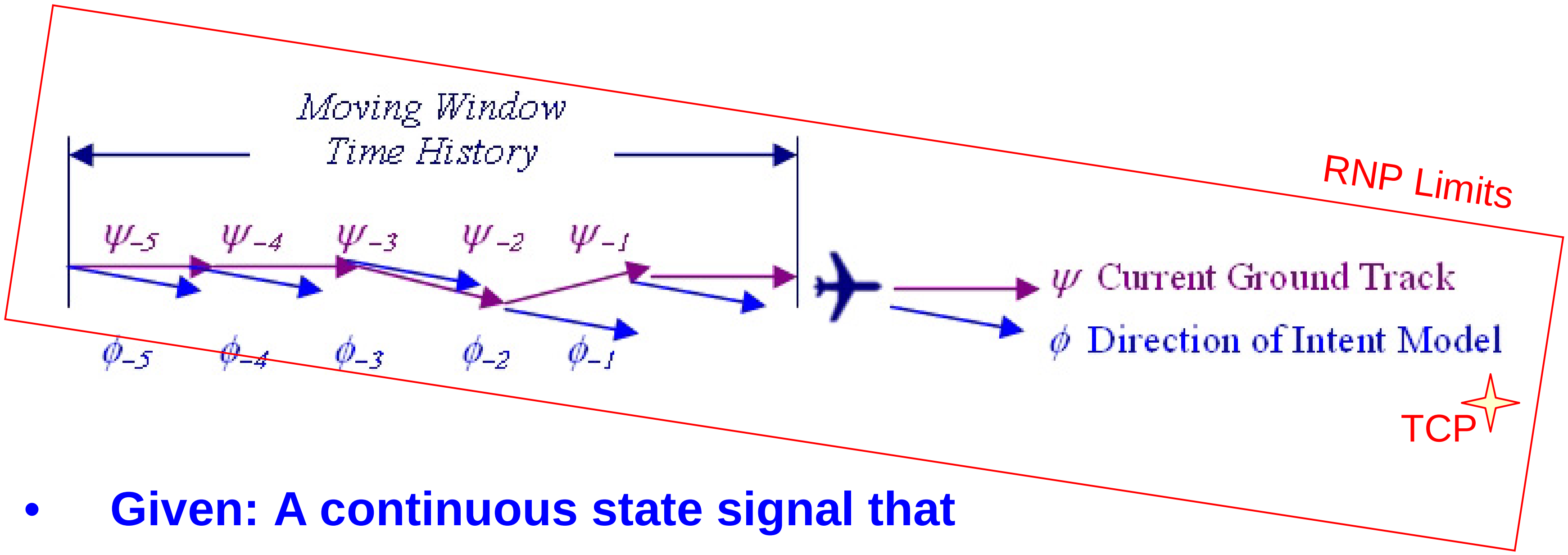
- Goal: Always have an Estimate of the Aircraft State

Electronic Considerations



- **Is the electronic signal coming from the right direction?**
- **Need:**
  - **A directional antenna capable of determining the direction from which the ADS-B signal arrived, or**
  - **Multilateration to determine where the signal arrived**

ADS-B State and Intent Verification



- **Given: A continuous state signal that is coming from the correct direction**
- **Verification Questions:**
  - **Are the Data in the Moving Window History within the RNP for tracking the next TCP?**
  - **Is the Intent of the Pilot to Go To the TCP?**

Mathematical Correlation Functions

- **Mathematics:**

Local $L(t) \text{ or } L(s)$

Global $\frac{1}{k} \int_{flight\ path} L(s)\, ds$

Local Correlation defined for an instant of time (t) of for a specific point (s)

Global Correlation defined for a history of time (t) bounded by some start & current time

We like a Local Correlation to be bounded by definition

*** Based on: Krozel, J. and Andrisani, D., "Intelligent Path Prediction for Vehicular Travel", *IEEE Systems, Man, and Cybernetics*, Vol. 23, No. 2, March/April, 1993.**

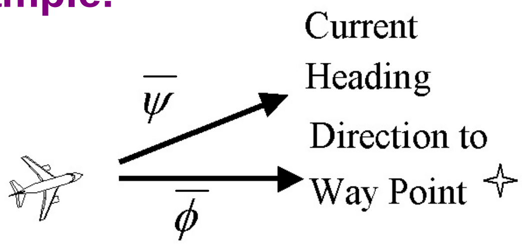
Intent Verification – Correlation Functions

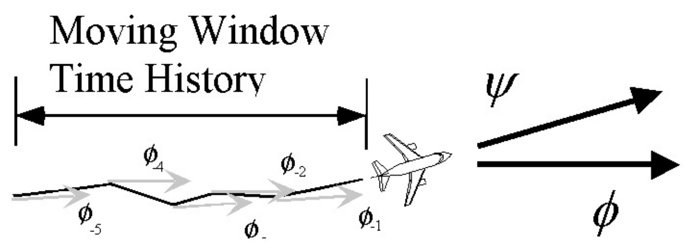
- **Mathematics:**

Local $\vec{\psi} \cdot \vec{\phi}$

Global $\frac{1}{k} \int_{flight\ path} \vec{\psi} \cdot \vec{\phi}\, ds$

- **Example:**





-1 < Local Correlation < 1
by definition

-1 < Global Correlation < 1
by choice of k

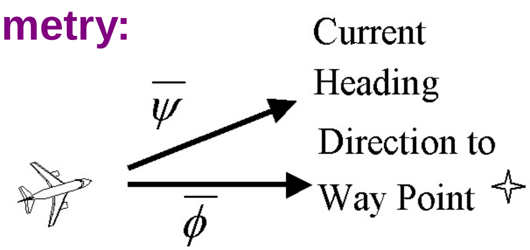
*** Based on: Krozel, J. and Andrisani, D., "Intelligent Path Prediction for Vehicular Travel", *IEEE Systems, Man, and Cybernetics*, Vol. 23, No. 2, March/April, 1993.**

Intent Verification – Correlation Functions

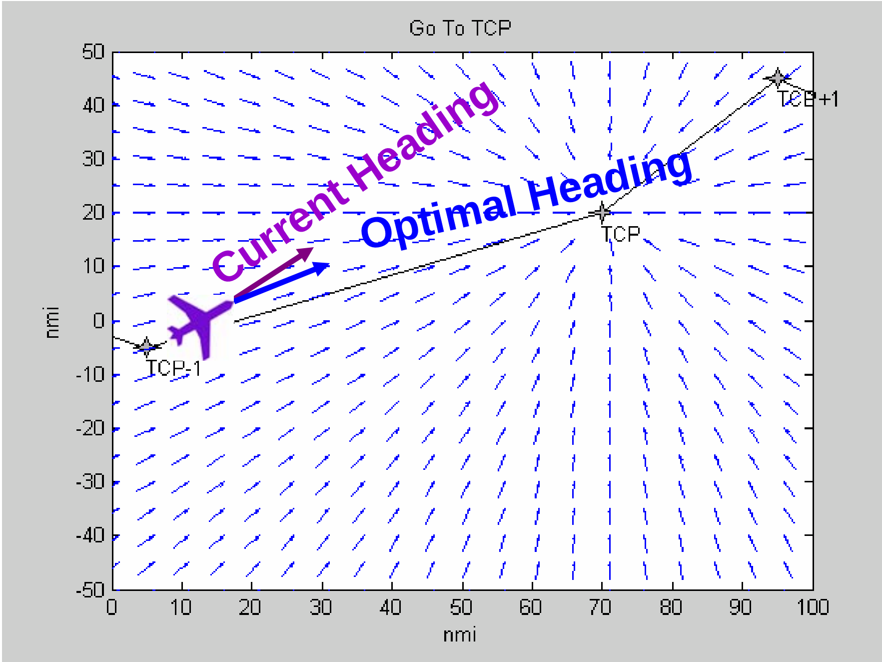
- **Mathematics:**

  Local $\vec{\psi} \cdot \vec{\phi}$

- **Geometry:**



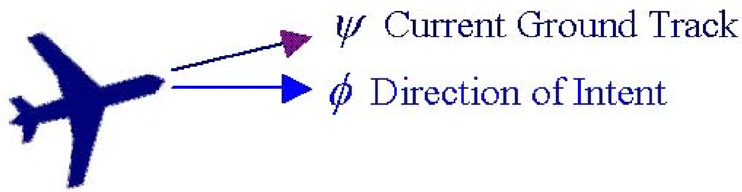
-1 < Local Correlation < 1 by definition



Discrete Time Local Correlation Functions

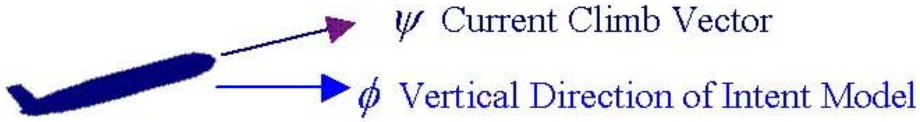
Local Correlation

- **Horizontal:**



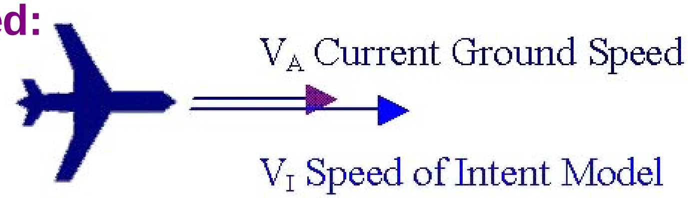
$$L(i) = \hat{\Psi}(i) \cdot \hat{\phi}(i)$$

- **Vertical:**



$$L(i) = \hat{\Psi}(i) \cdot \hat{\phi}(i)$$

- **Speed:**



$$L(i) = \frac{V_{actual}(i)}{V_{\mathrm{intent}}(i)}$$

Horizontal and Vertical dimensions intuitively combine in 3D; Speed dimension naturally describes progression in time along a 3D path

Discrete Time Global Correlation Functions

- **Recursive Format Equations aid in Discrete Time Implementation**
- **Basic Global Correlation Function:** ($t=N\Delta$ the N-th time increment of duration Δ)

$$\rho(N)=\frac{1}{N}\sum_{\mathrm{i}=1}^{\mathrm{N}}L(i)=\frac{N-1}{N}\left\{\rho(N-1)+\frac{1}{N-1}L(N)\right\}$$

- **Moving Window Average:** (M data points constitute the Memory)

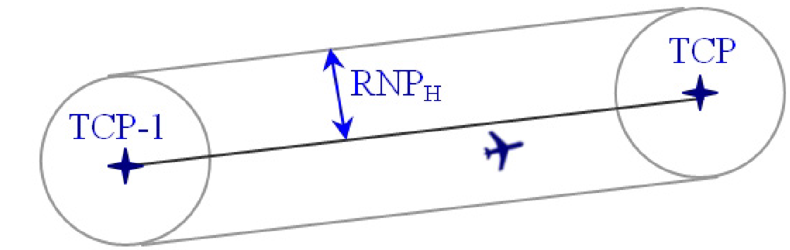
$$\rho_M(N)=\frac{1}{M}\sum_{i=N-M+1}^{N}L(i)=\frac{N}{M}\rho(N)-\frac{N-M}{M}\rho(N-M)$$

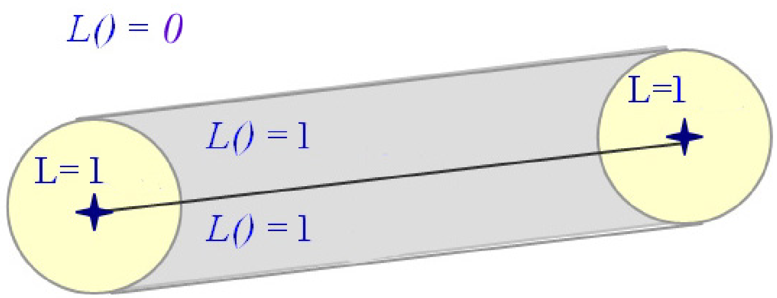
- **Fading Memory:** *(fading factor 0<f<1)*

$$\rho_f(N)=\frac{1}{G_N}\sum_{i=1}^{N}f^{N-i}L(i)=\frac{G_{N-1}}{G_N}\left\{f\rho_f(N-1)+\frac{L(N)}{G_{N-1}}\right\}$$

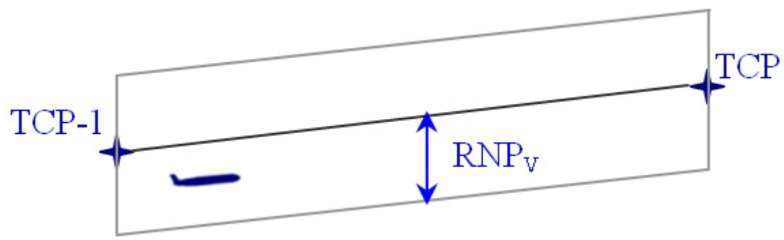
Geometric Conformance

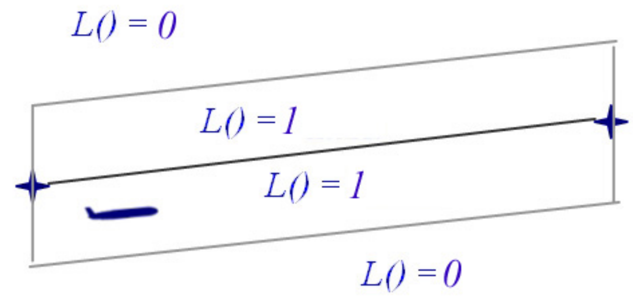
- **Horizontal:**





- **Vertical:**



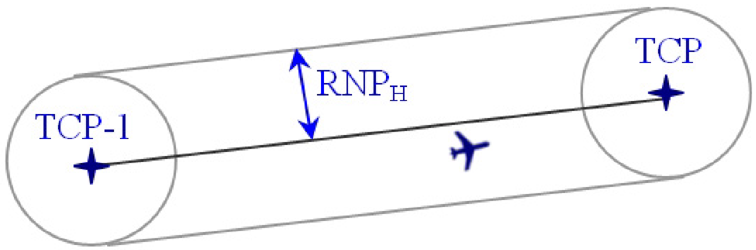


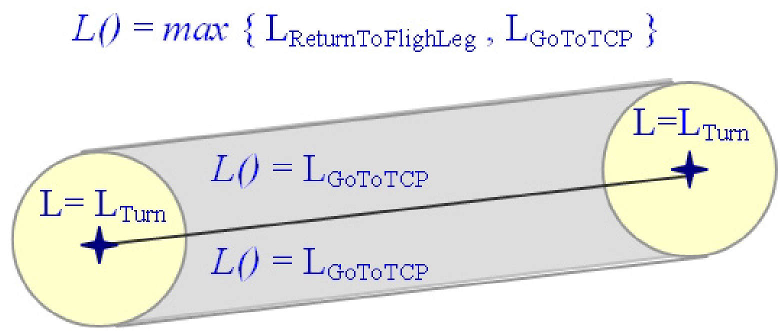
Certainty Factors:

$$CF_{Path} = \frac{1}{2}\left[\rho_{Horiz} + \rho_{Vertical}\right] \qquad CF_{Speed} = \left|\rho_{Speed} - 1\right| + 1$$

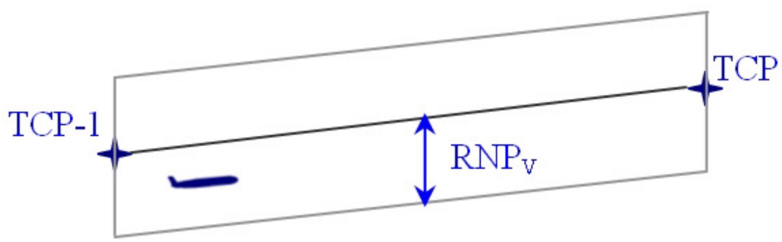
Intent Conformance

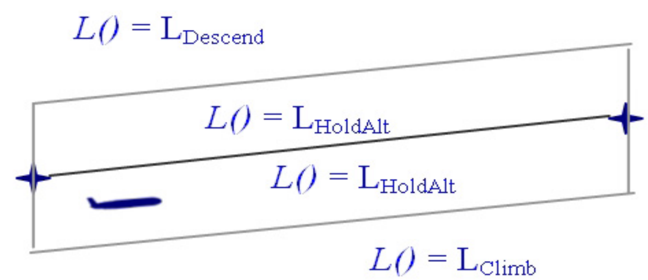
- **Horizontal:**





- **Vertical:**





Certainty Factors:

$$CF_{Path} = \frac{1}{2}\left[\rho_{Horiz} + \rho_{Vertical}\right] \qquad CF_{Speed} = \left|\rho_{Speed} - 1\right| + 1$$

Signal Conformance

- Define a unit vector $\hat{\psi}_{Signal}$ in the direction to the incoming electronic signal
- Define the unit vector $\hat{\phi}_{Aircraft}$ from the receiver location to the aircraft as specified by the ADS-B TC Report
- The local correlation

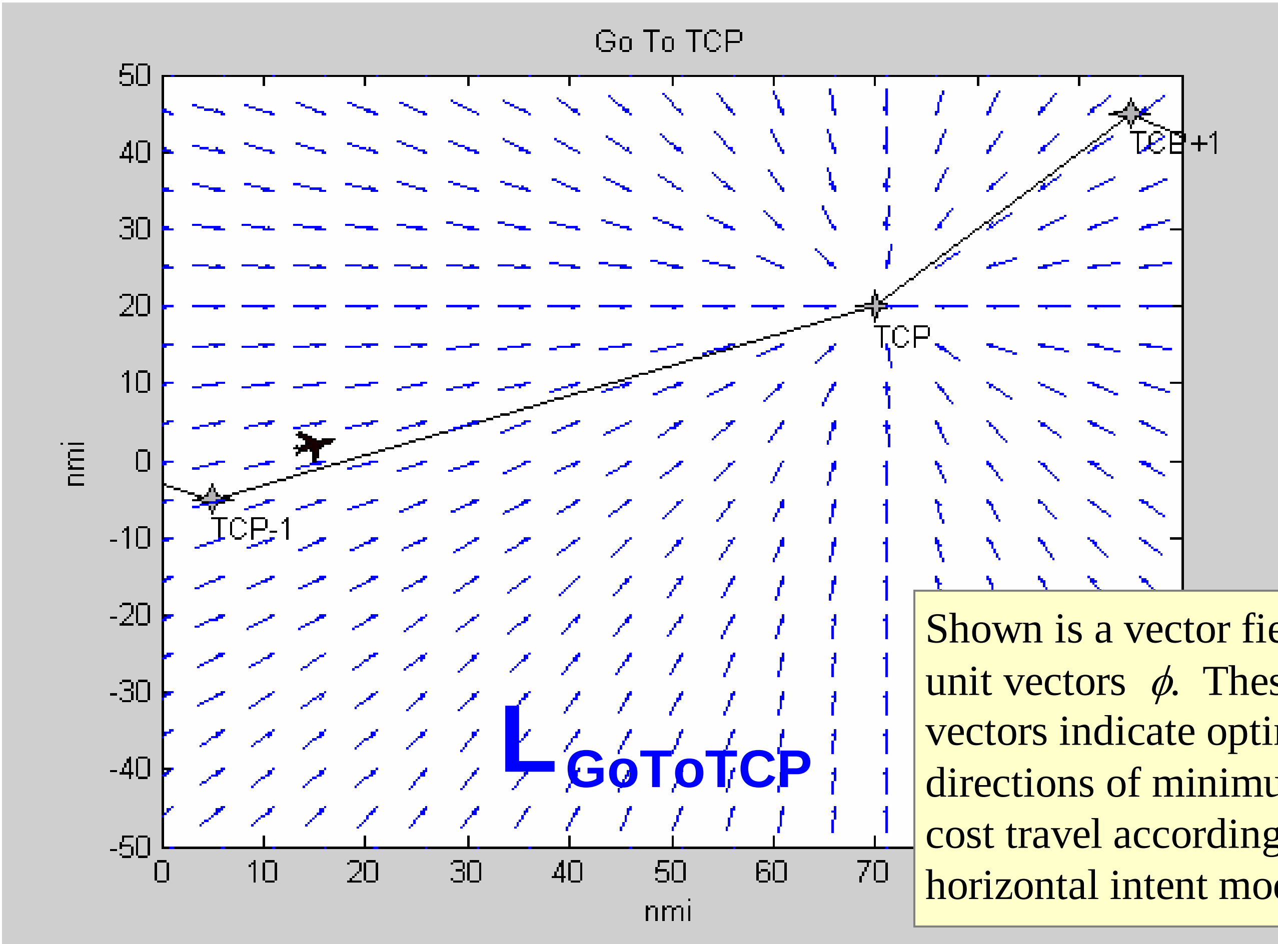
$$L_{Electronic} = \hat{\psi}_{Signal} \cdot \hat{\phi}_{Aircraft}$$

indicates (locally) if the signal is arriving from the same direction as the aircraft is reported to be.

Primitive Intent Models used in Correlation Functions

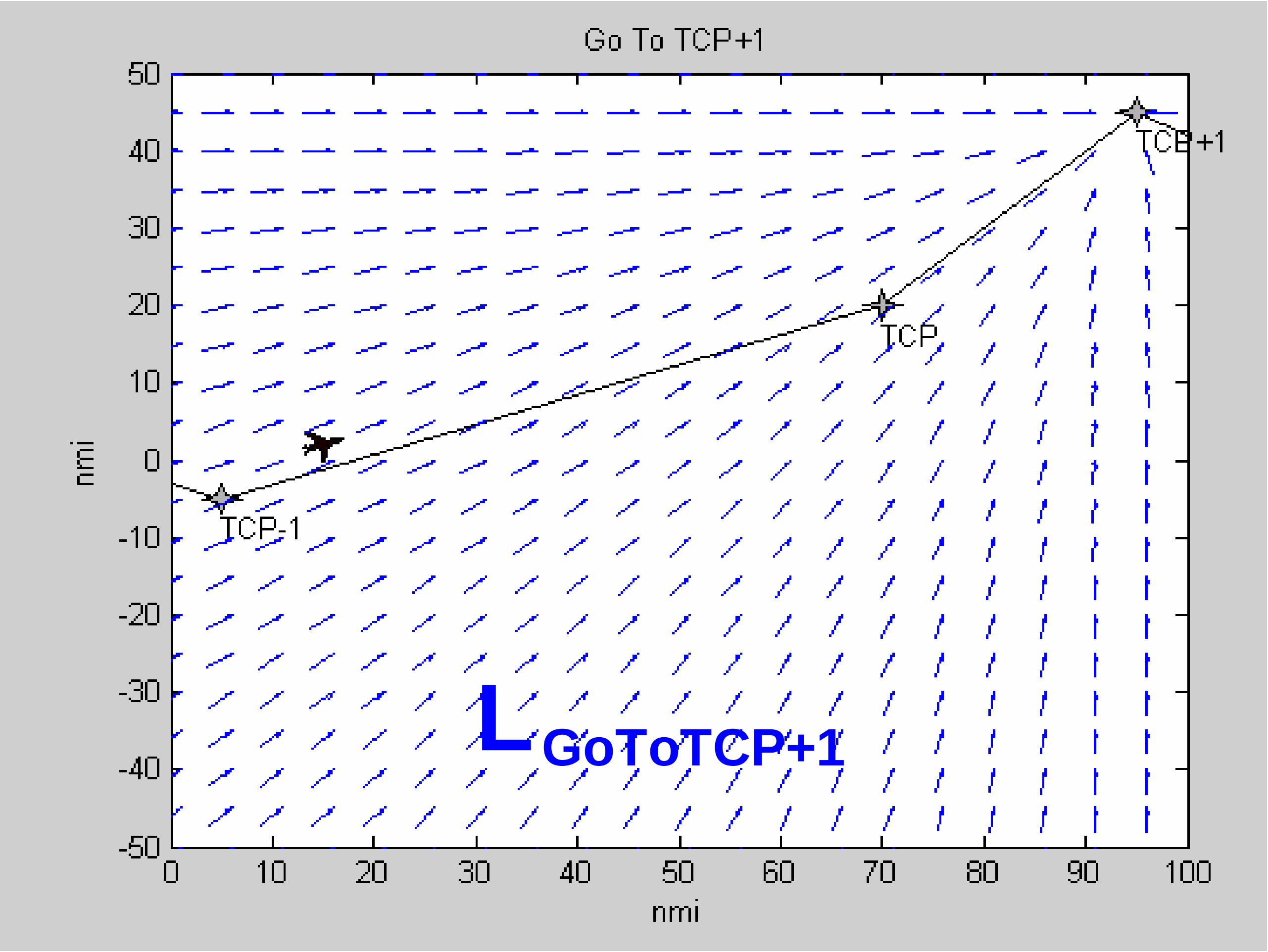
Horizontal, Vertical, or Speed Intent Description	Dimension	Intent Status
Direct to TCP (or TCP+1)	Horizontal	Steady State
Return to Flight Leg from TCP-1 to TCP	Horizontal	Steady State
Return to Flight Leg from TCP to TCP+1	Horizontal	Steady State
Hold Coordinated Turn Left (-1.5°/sec or -3°/sec turn rate)	Horizontal	Transient
Hold Coordinated Turn Right (1.5°/sec or 3°/sec turn rate)	Horizontal	Transient
Hold TCP Altitude	Vertical	Steady State
Hold TCP+1 Altitude	Vertical	Steady State
Climb/Descend to TCP Altitude	Vertical	Steady State
Climb/Descend to TCP+1 Altitude	Vertical	Steady State
Speed to Meet TCP Time-To-Go (TTG) Requirement	Speed	Transient
Speed to Meet TCP+1 Time-To-Go (TTG) Requirement	Speed	Transient

Primitive Intent Model – Go To TCP

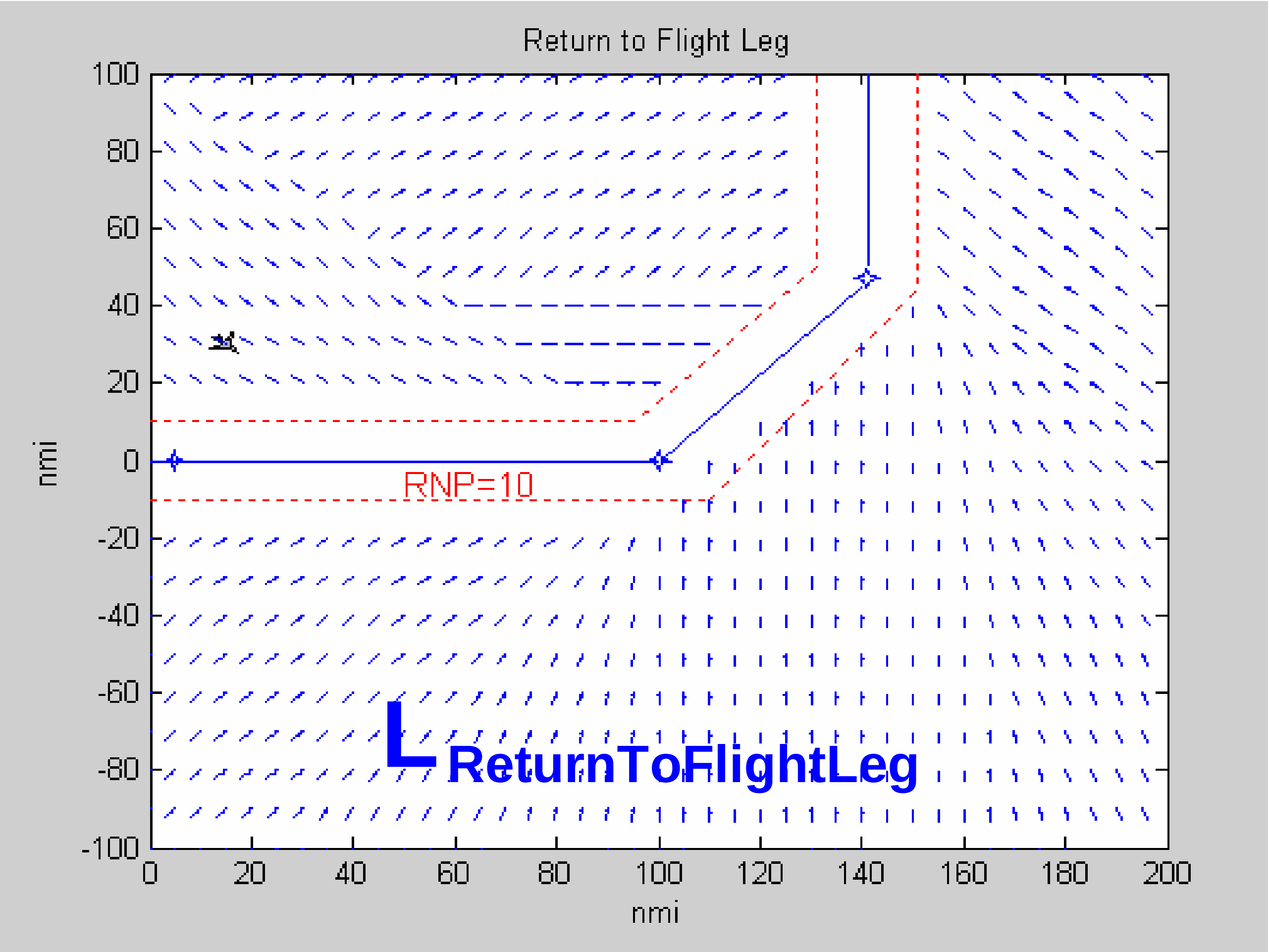


Shown is a vector field of unit vectors ϕ. These vectors indicate optimal directions of minimum cost travel according to a horizontal intent model.

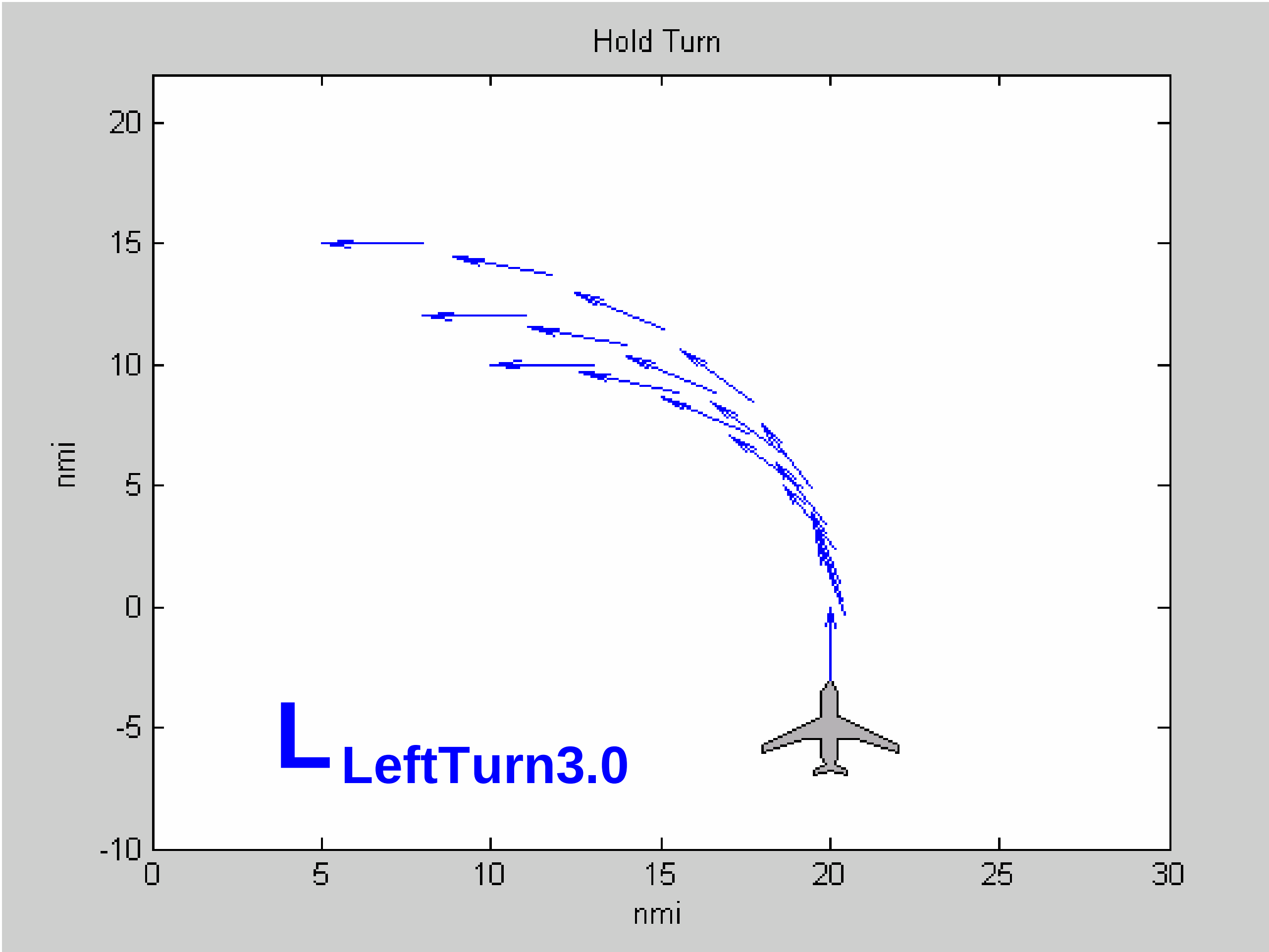
Primitive Intent Model – Go To TCP+1



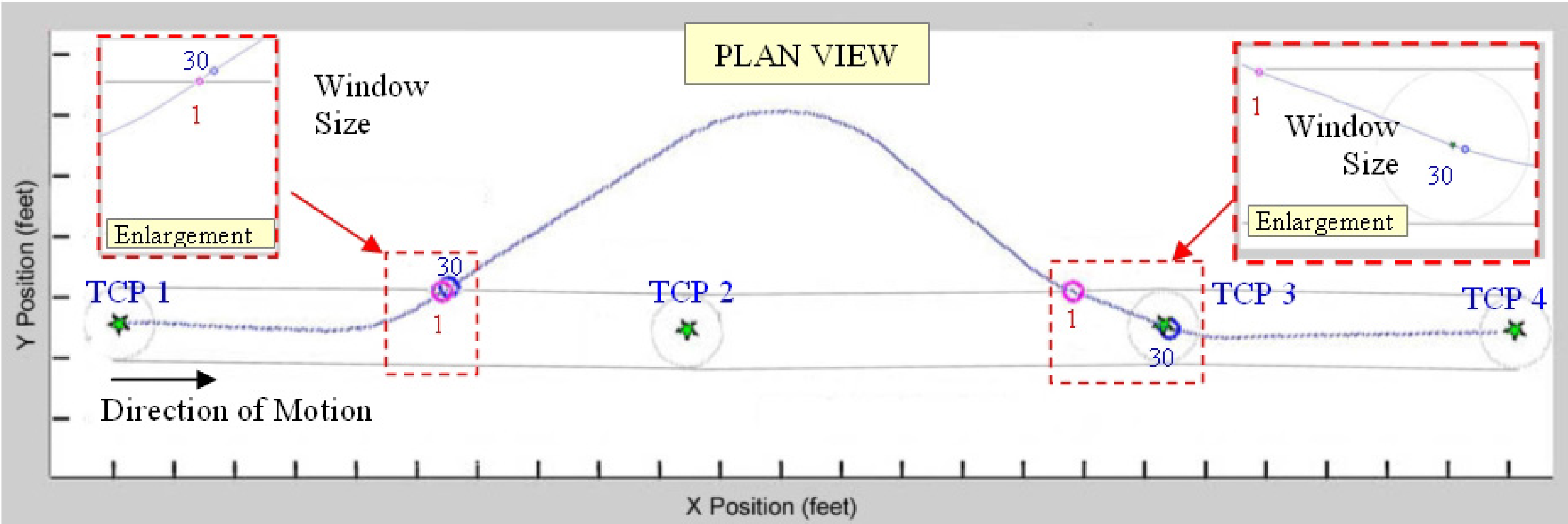
Primitive Intent Model – Return to Flight Leg



Primitive Intent Model – Hold Turn Rate Left



Geometric Conformance Example

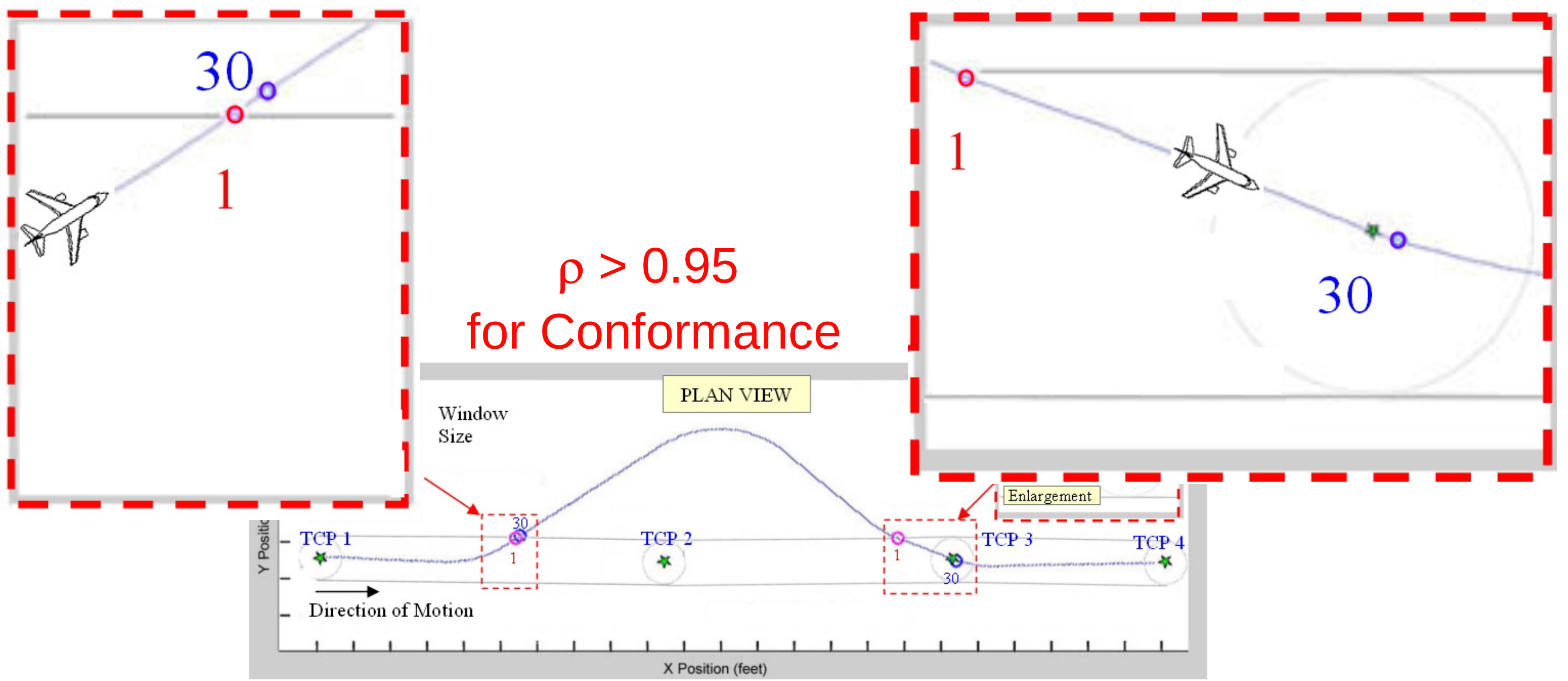


- **RTCA: RNP-1 specifies that the RNAV system is certified to stay within 1 nmi of the intended lateral routing at least 95% of the time, including the time during turns**
- **Criteria for Geometric Conformance:** $\rho > 0.95$
- **Depends on the Moving Window Size**

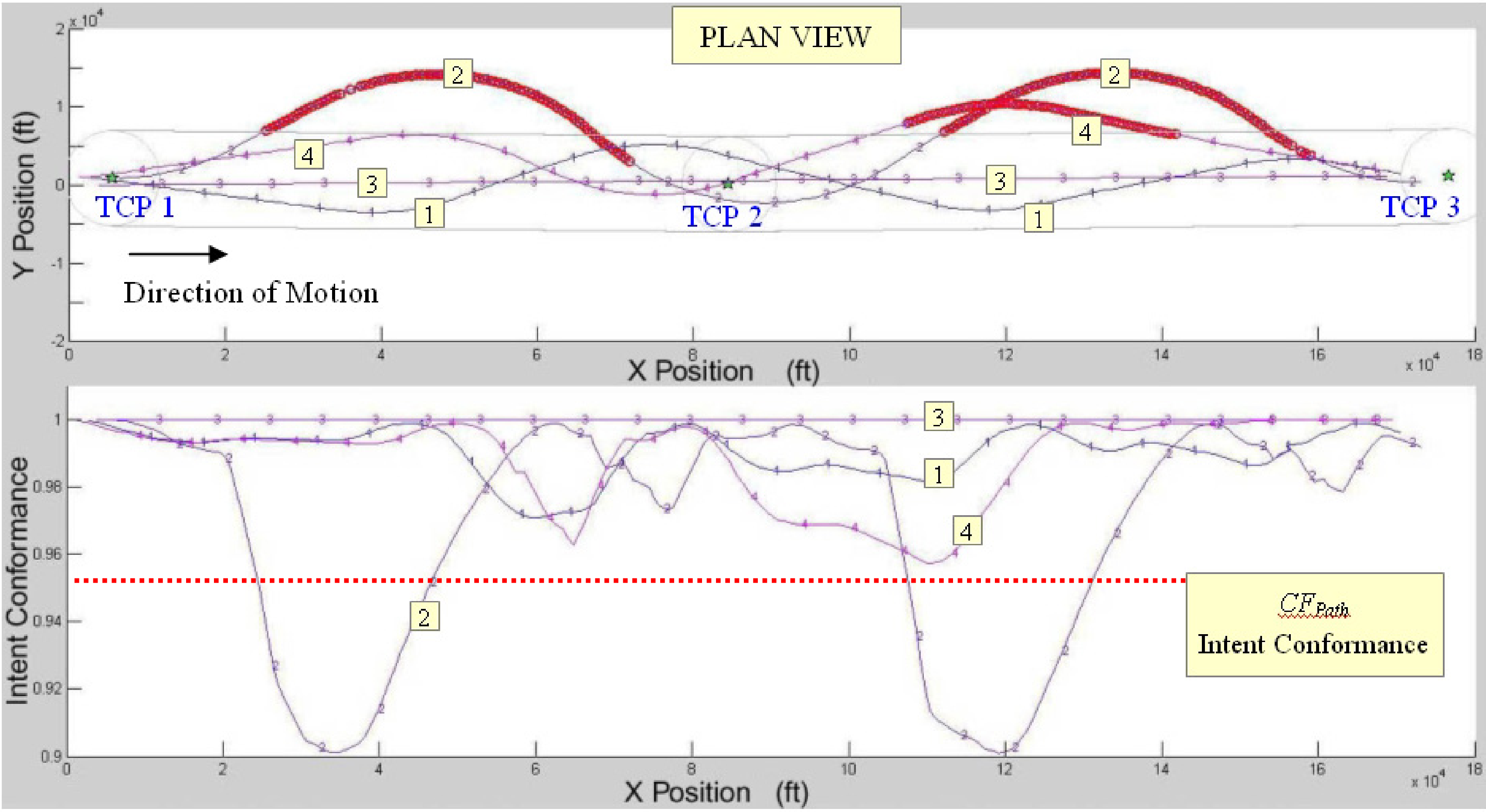
Geometric Conformance Depends on Moving Window Size

Exiting: **Most of the data History in Conformance 95% → 1/10 points out of conformance, 1/20, 2/30, 2/40, 3/50, etc.**

Entering: **Most of the data History out of Conformance 95% → Need 10/10 points in conformance, 20/20, 29/30, 39/40, 48/50, etc.**



Geometric and Intent Conformance Example



- **Intent Conformance provides derivative information that is not in the geometric conformance calculation**

Conclusion

- **ADS-B V&V: There is a need for ADS-B signals to be validated for a safe and reliable source of surveillance information**
- **State Verification: State verification requires that continuous aircraft state data can be achieved in the presence of noise, data dropouts, and erroneous data (with practical limits of Kalman filter technology)**
- **Intent Verification: Intent verification requires that geometric and intent conformance be checked against some standard**
- **Signal Verification: Requires that the electronic signal arrive at the directional receiving antenna from the expected direction**
  - **It may be easier for Ground Applications to provide directional antenna then for Airborne applications**
- **Research is on-going**

References

ADS-B (RTCA Documents):

- **ADS-B Minimum Aviation System Performance Standards (MASPS) DO242 and DO242A**
- **MASPS for Aircraft Surveillance Applications (ASA) DO289**
- **ADS-B Minimum Operational Performance Standards (MOPS) 1090 MHz DO260 and DO260A**
- **Mode S MOPS DO-181c which includes ADS-B DF17 message**
- **UAT MOPS: DO-282**

Target Tracking / Kalman Filtering (Books):

- **Gelb, *Applied Optimal Estimation***
- **Maybeck, *Stochastic Models, Estimation, and* Control**
- **Mendell, *Lessons in Estimation Theory***

Intent Inference / Conformance Monitoring (Conf./Journal):

- **Krozel & Andrisani – Purdue University**
- **Reynolds – M.I.T.**